

# **Microstructural evolution of Ti-6Al-4V during high strain rate conditions of metal cutting**

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## **Abstract**

The microstructural evolution following metal cutting was investigated within the metal chips of Ti-6Al-4V. Metal cutting was used to impose a high strain rate on the order of  $\sim 10^5 \text{ s}^{-1}$  within the primary shear zone as the metal was removed from the workpiece. The initial microstructure of the parent material (PM) was composed of a bi-modal microstructure with coarse prior  $\beta$  grains and equiaxed primary  $\alpha$  located at the boundaries. After metal cutting, the microstructure of the metal chips showed coarsening of the equiaxed primary  $\alpha$  grains and  $\beta$  lamellar. These metallographic findings suggest that the metal chips experienced high temperatures which remained below the  $\beta$  transus temperature.

Keyword: metal cutting, Ti-6Al-4V, grain refinement

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# Outline

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- ☐ Introduction
- ☐ Experimental Method
- ☐ Results
- ☐ Summary
- ☐ Future Works

# Objective

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- ❑ Utilized metal-cutting to subject material to strain rates in the range of  $10^3$  to  $10^5 \text{ s}^{-1}$
- ❑ Evaluated the microstructure response of Ti-6Al-4V to high strain rate conditions above  $10^3 \text{ s}^{-1}$
- ❑ Investigated the response of the deformed microstructure to subsequent heat treatments

# Ti-6Al-4V

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- ❑ Titanium and its alloys has been widely applied in the aerospace, chemical, biomedical industry.
- ❑ Ti-6Al-4V is one of the most used titanium alloys.
- ❑ Young's Modulus: 114 GPa; Ultimate Tensile Strength: 1170 MPa; Specific Heat Capacity: 0.5263 J/g-°C
- ❑ It is a two phase microstructure ( $\alpha$  Ti +  $\beta$  Ti)
  - $\alpha$  Ti: hexagonal close-packed (hcp) structure
  - $\beta$  Ti: body-centered cubic (bcc) structure
- ❑ Beta transus temperature:  $\sim 995^{\circ}\text{C}$

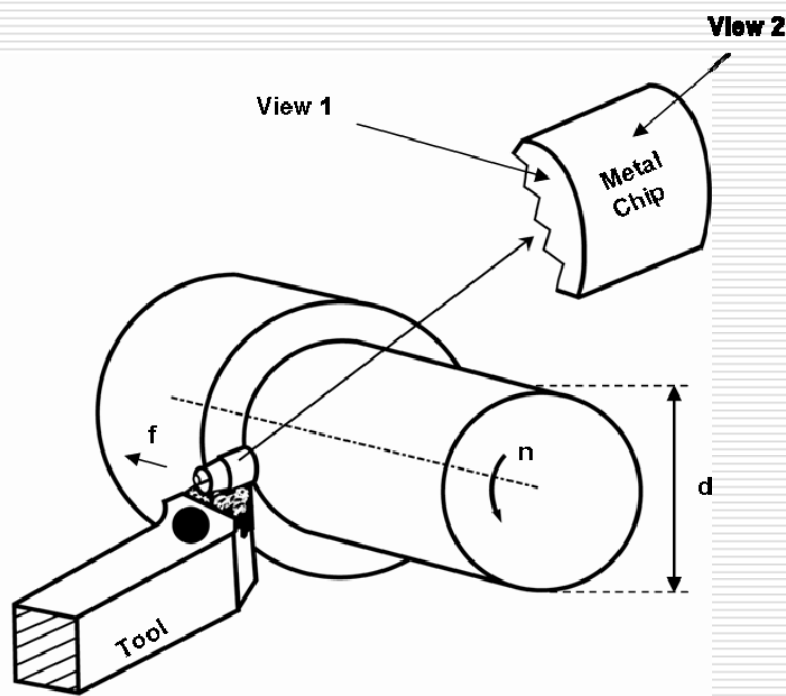
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$$\tan \phi = \frac{\frac{t}{c} \cos \alpha}{1 - \frac{t}{c} \sin \alpha}$$

# A turning process can be used to approximate orthogonal cutting conditions

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Cutting parameters:

Rake angle :  $+5^\circ$

Depth of cut :  $360\mu\text{m}$

Travel velocity :  $0.22 \sim 0.57 \text{ m/s}$

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Estimated shear strain rate:

$1 \sim 2 \times 10^5 \text{ s}^{-1}$

Estimated shear strain:  $\sim 5$

***Schematic of turning operation with chip morphology***

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# Heat Treatment Schedule

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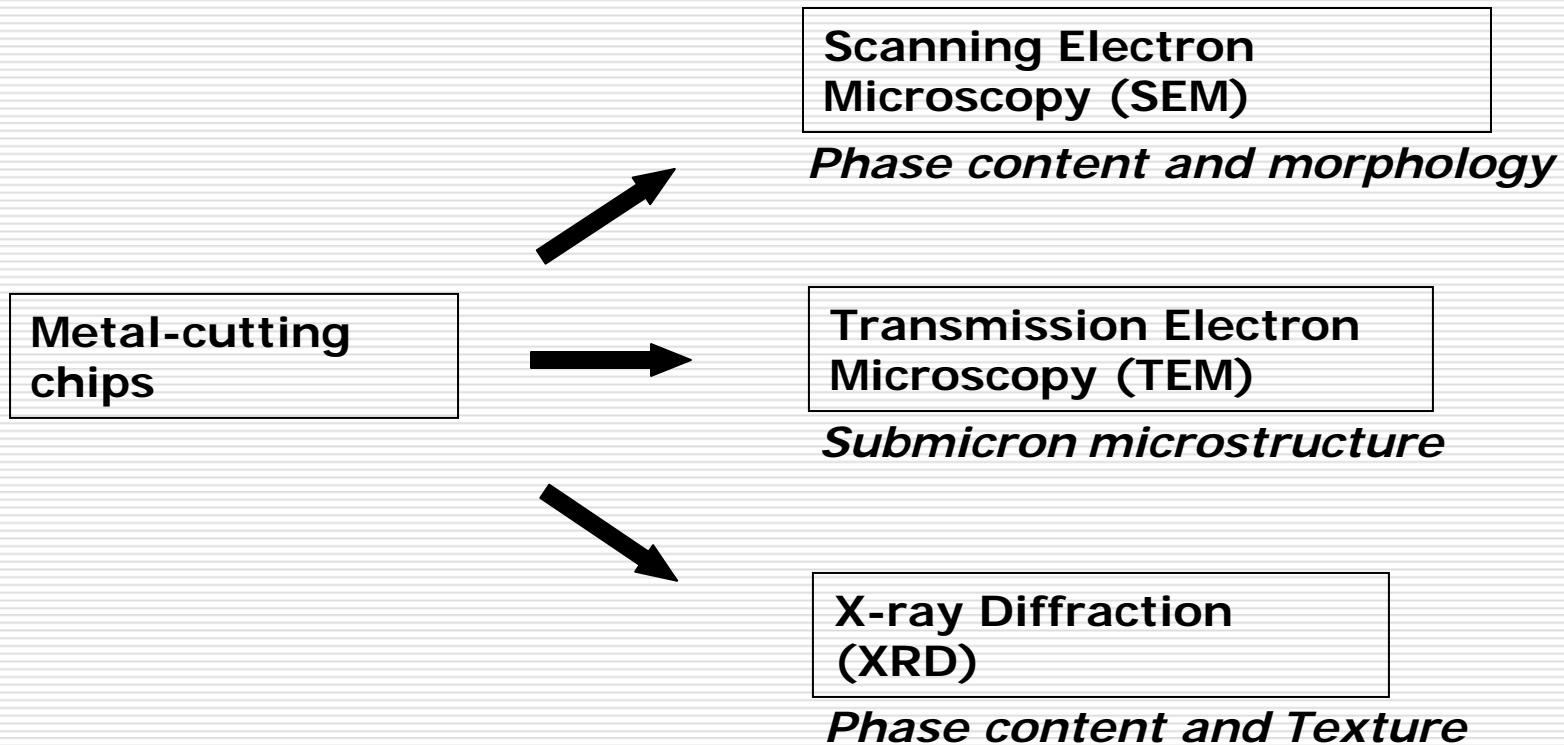
- ❑ Heat treat as-cut metal chips at 260°C and 730°C for 5, 15, 30 and 90 minutes, respectively.
- ❑ 260°C was selected to study the low temperature microstructural response.
- ❑ 730°C was selected as the beginning temperature range of the  $\alpha$  to  $\beta$  phase transformation.



# Metallurgical Study

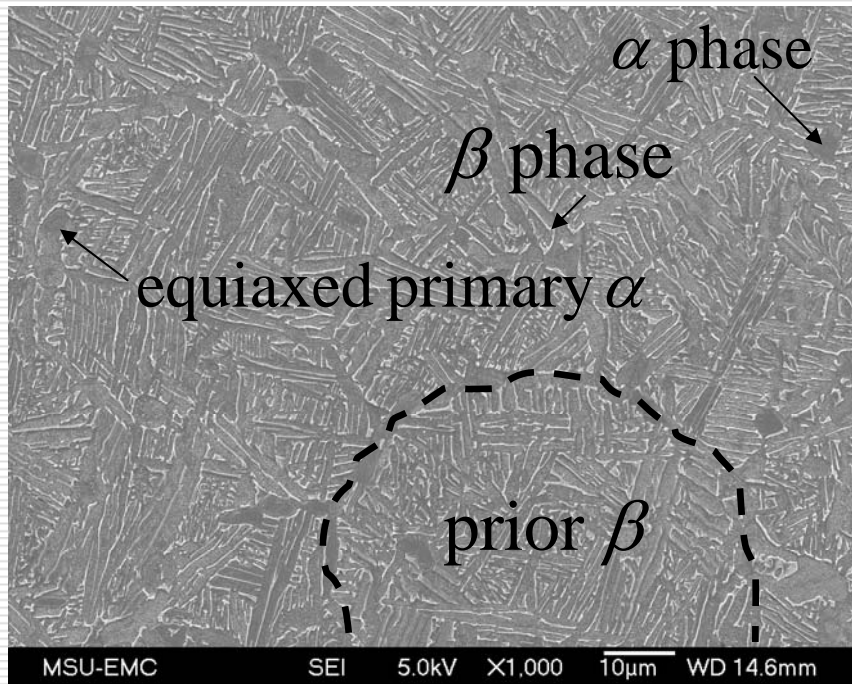
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- ❑ Cut metal chips were characterized using variety of characterization techniques.



# As-received parent material shows a bi-modal microstructure

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width of  $\alpha$  laths: 1.0  $\mu$ m

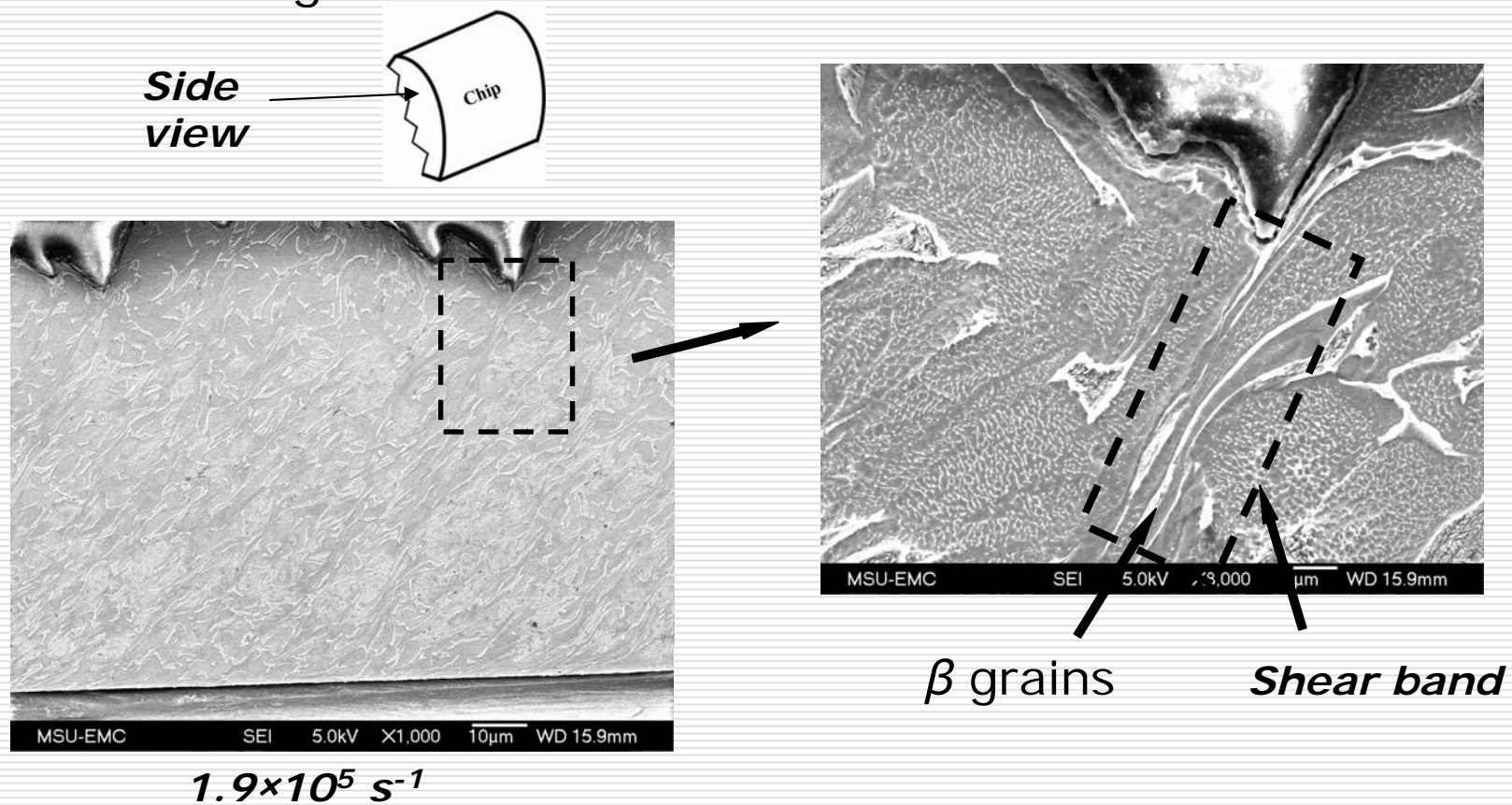
equiaxed primary  $\alpha$ : 5.2  $\mu$ m

prior  $\beta$ : 50  $\mu$ m

volume fraction of  $\beta$  phase: 12 ~ 13%

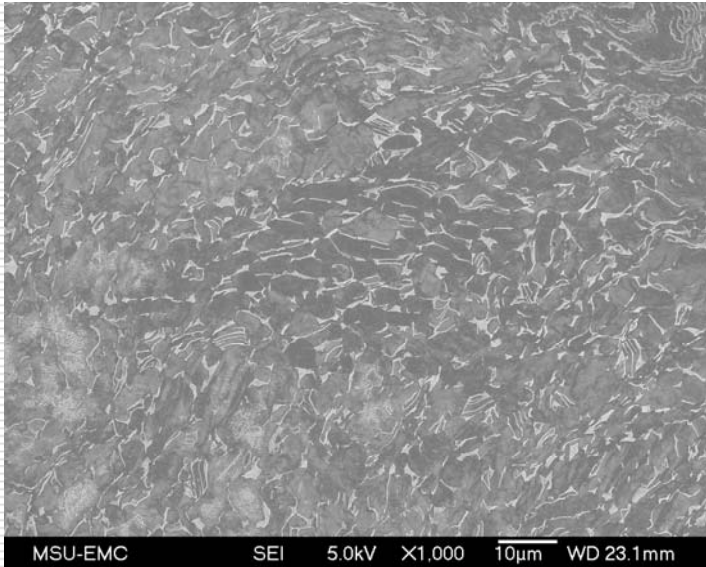
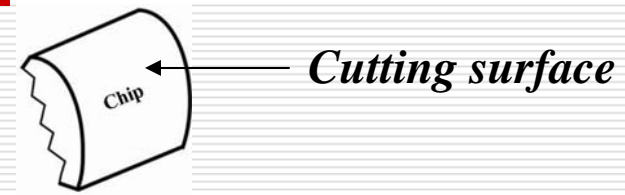
# Evidence of non-homogenous shear bands observed in side view

## □ SEM images

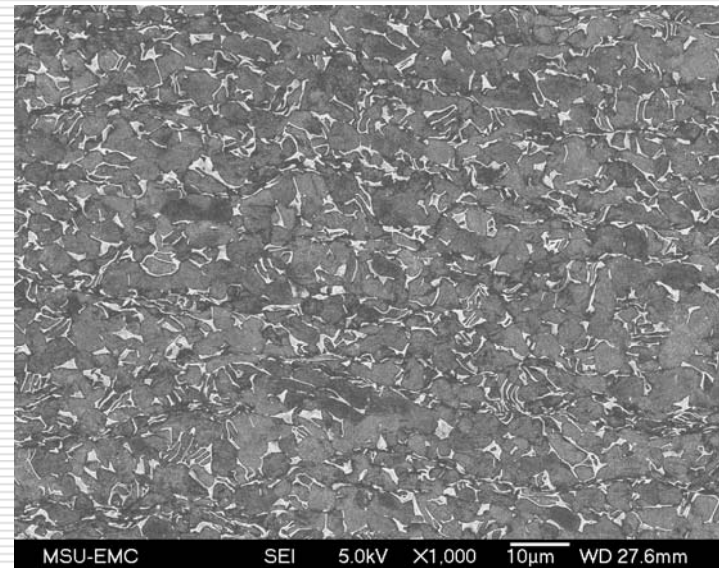


# No change in grain size observed on cutting surface

## □ SEM images



$1.1 \times 10^5 \text{ s}^{-1}$

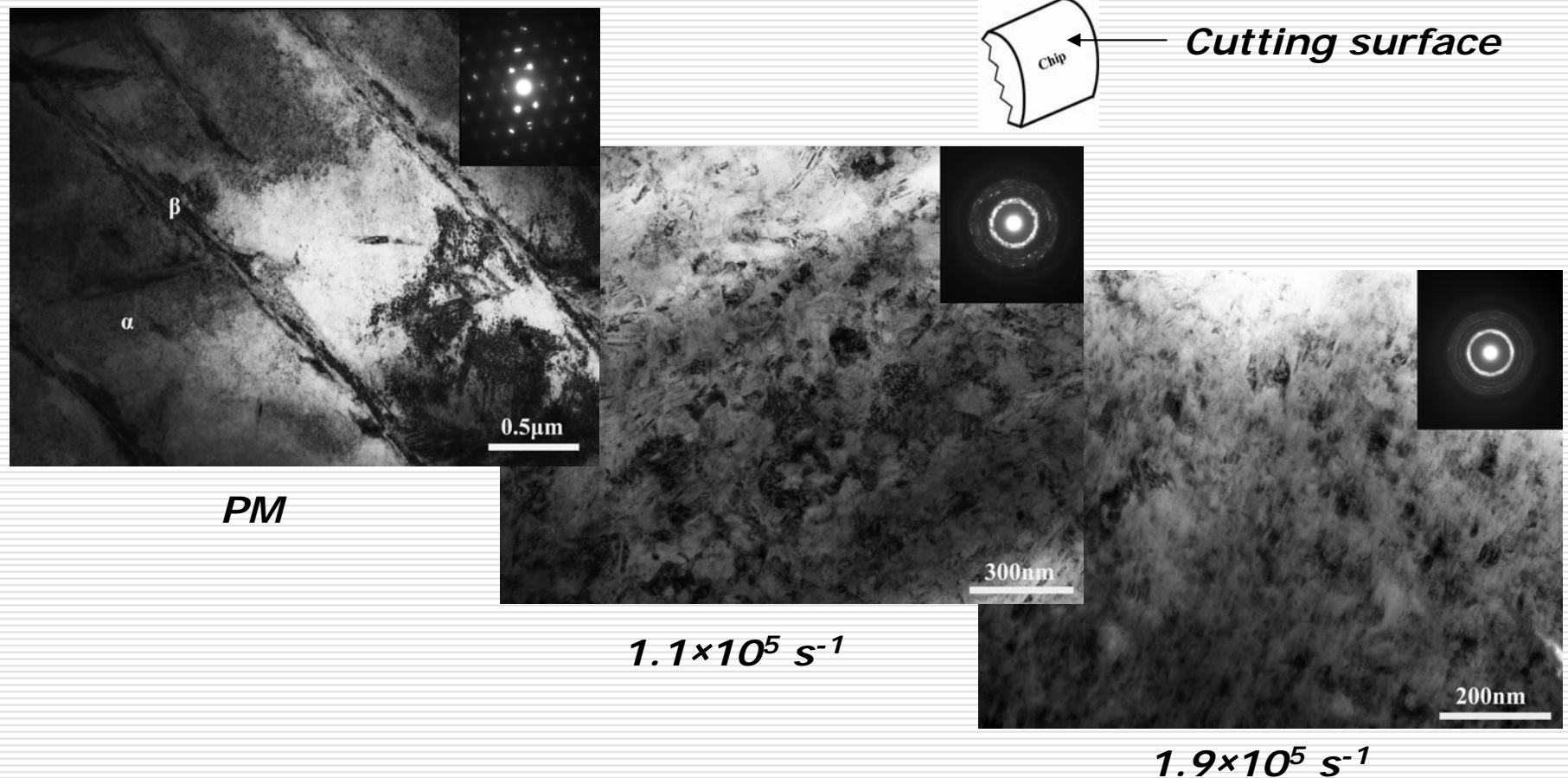


$1.9 \times 10^5 \text{ s}^{-1}$

Equiaxed  $\alpha$  grain =  $4.8 \sim 5.1 \mu\text{m}$

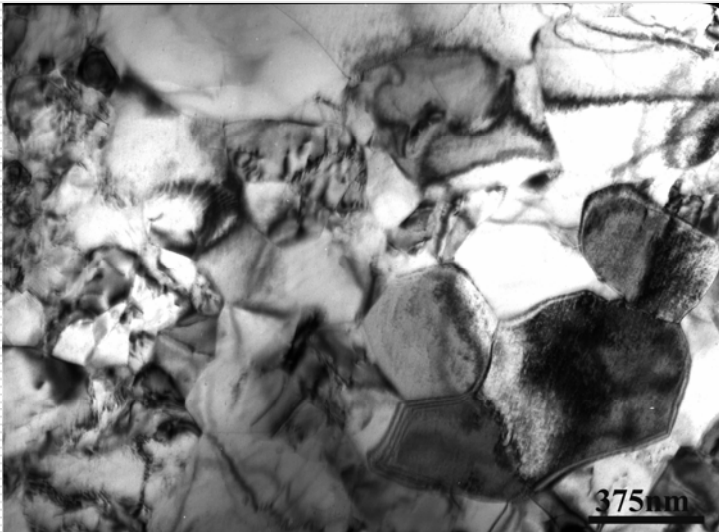


# Evidence of nano-crystalline microstructure observed in TEM/SAD



# TEM micrograph of heat treated metal-cutting chips

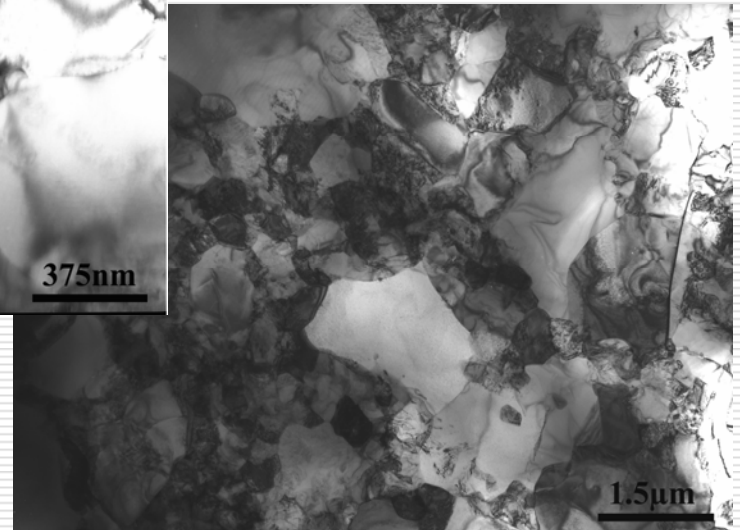
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*5 min*



*30 min*

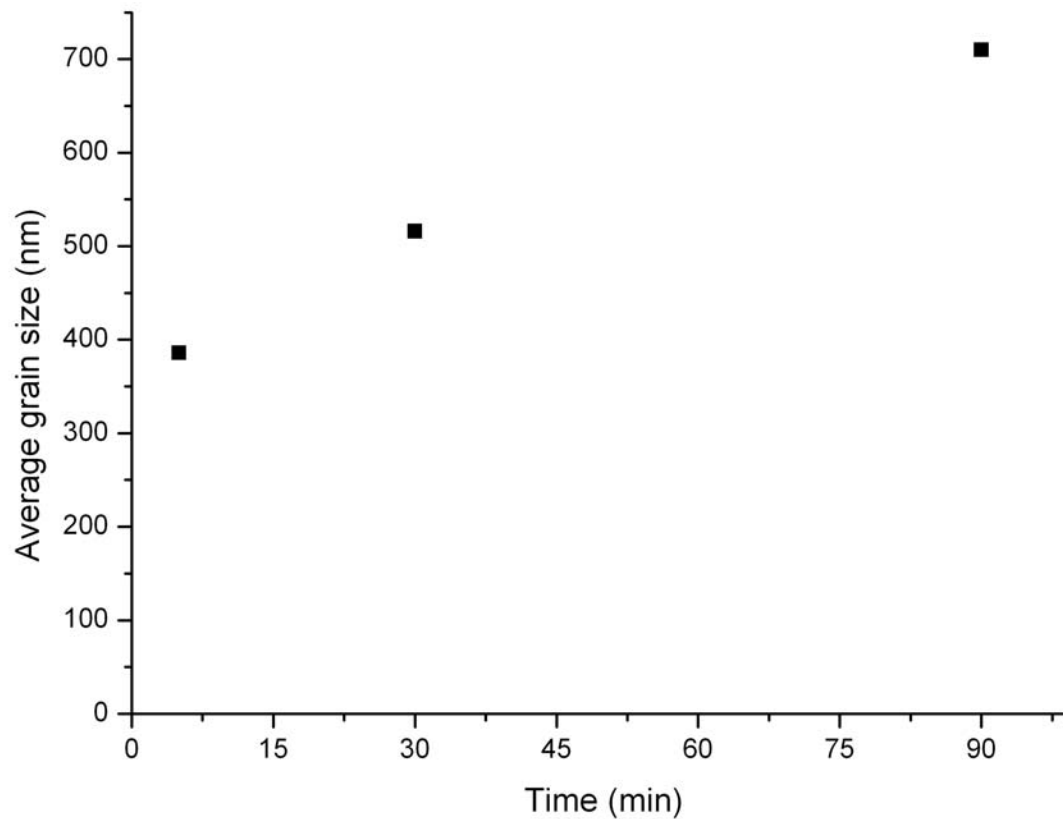


*90 min*

*Heat treated at 730°C*

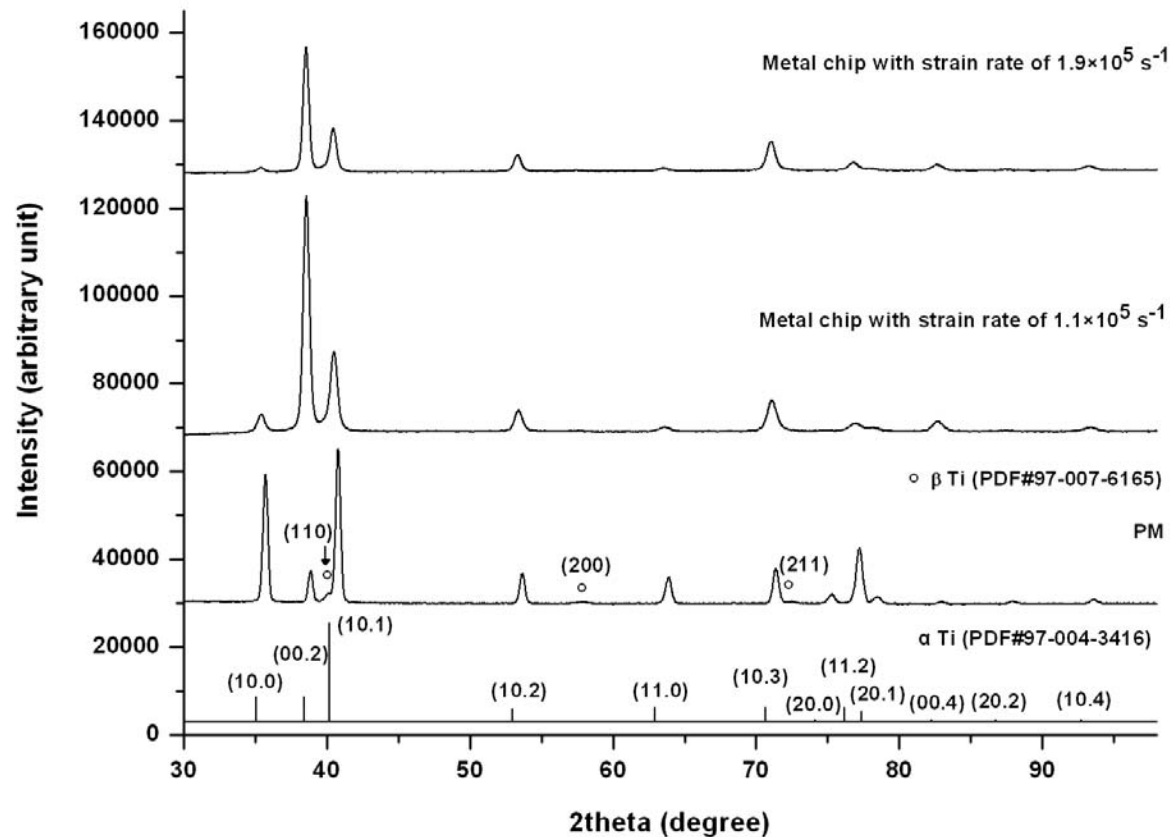
# Grain growth rate of $\alpha$ phase

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***Heat treated at 730°C***

# A change in rolling texture of the $\alpha$ phase is observed after the metal cutting process





# XRD Summary shows minor peak broadening

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| hkl    | <i>PDF#</i><br>97-004-3416 | PM     |       | strain rate =<br>$1.1 \times 10^5 \text{ s}^{-1}$ |       | strain rate =<br>$1.9 \times 10^5 \text{ s}^{-1}$ |       |
|--------|----------------------------|--------|-------|---|-------|---|-------|
|        |                            |        | FWHM  |   | FWHM  |   | FWHM  |
| (10.0) | 35.089                     | 35.691 | 0.357 | 35.320  | 0.533 | 35.285  | 0.501 |
| (00.2) | 38.449                     | 38.842 | 0.337 | 38.534  | 0.465 | 38.510  | 0.426 |
| (10.1) | 40.178                     | 40.771 | 0.366 | 40.447  | 0.564 | 40.402  | 0.502 |

# Summary

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- ❑ Microstructure observation shows an evolution from initial bi-modal microstructure to equiaxed  $\alpha$  grains with intergranular  $\beta$  grains.
- ❑ The resulting microstructure suggests that the  $\beta$  transus was not exceeded during the metal cutting.
- ❑ Microstructural analysis indicates a non-homogenous grain refinement has occurred within the shear band region.
- ❑ The heat treatment experiment indicated the formation of nano-crystalline and refined grains have good thermo-stability up to 730°C

# Acknowledgements

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- **AFOSR Grant # FA9550-07-1-0282 under the direction of Dr. Joan Fuller.**